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A Comparison of the Corrosion and Stress Corrosion Resistance of Two Depleted Uranium Alloys; DU-0.75 Ti and DU-2 Mo

PATRICIA P. TRZASKOMA

Material Science and Technology Division

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Considerable experimental work concerning the corrosion rates, stress corrosion behavior, and effects of corrosion on the mechanical properties of depleted uranium alloys has been performed. In this study data for two alloys, DU-0.75 Ti and DU-2 Mo, in three environments have been collected and compared in order to determine whether there are significant differences in their corrosion characteristics and whether these differences warrant a choice of alloy for kinetic energy penetrator applications. In moist air the corrosion rates of the two alloys are low and appear to be of little consequence with respect to this application. In salt fog the corrosion rate of DU-3/4 Ti increases		

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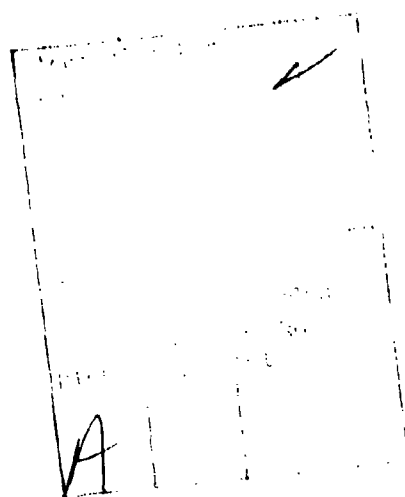
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20 ABSTRACT (Continued)

sharply. The weight loss in thirty days is about 7% of the total weight. No data was found for the molybdenum alloy in salt fog. Further experimental work is suggested.

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A Comparison of the Corrosion and Stress Corrosion Resistance of Two Depleted Uranium Alloys; DU-0.75 Ti and DU-2 Mo

INTRODUCTION

Depleted uranium (DU) alloys are of especial interest to the military because of their excellent performance in armor defeating applications. Presently the Navy uses DU-2 Mo for the PHALANX penetrator and the Air Force uses DU-0.75 Ti for the GAU-8 penetrator. While the rationale for the Navy's selection of DU-2 Mo is somewhat unclear, the choice of DU-0.75 Ti by the Air Force was based on experimental work performed at the LOS ALAMOS SCIENTIFIC LABORATORIES wherein it was concluded that the titanium alloy shows better concluded corrosion resistance than the molybdenum alloy.

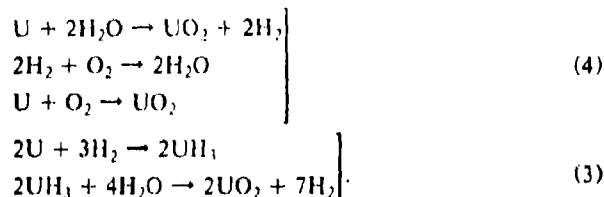
The purpose of the present study is to collate data from several experimental investigations concerning the corrosion, stress corrosion behavior, and effects of corrosion on mechanical and ballistic properties of the two alloys in order to determine whether any differences suggest a choice of alloy for future penetrator development.

BACKGROUND

Corrosion is the chemical reaction of a metal with its environment resulting in weight loss due to metal dissolution or weight gain due to the formation of adherent reaction products. Significant dimensional changes as a result of corrosion could affect the ballistic performance of penetrators, i.e., reduce penetration performance and accuracy due to weight loss, and cause gun jamming due to weight gain. In addition, pitting, or embrittlement due to the ingress of gaseous reaction products could result in changes in the mechanical properties of the metal, i.e., hardness or fracture resistance, which would also adversely affect penetrator performance.

Uranium reacts in air at room temperature with the formation of an oxide surface film and hydrogen. Under conditions of high humidity and at temperatures above 75 C corrosion accelerates and the film becomes nonadherent (1). The released hydrogen reacts with uranium resulting in the formation of solid UH_3 (2). The solid reaction product in moist air has been identified as $\text{UO}_{2.1}$, with 2-9% UH_3 depending upon the relative humidity (3). The bulk of the hydrogen produced therefore remains in the gas phase. The corrosion of uranium is also observed to depend upon the availability of oxygen. When the oxygen concentration decreases the corrosion rate increases. Baker et al. (4) have found that the free oxygen combines with released hydrogen to form H_2O . The possible reactions occurring when uranium is exposed to moist air can be summarized by the following set of equations:

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Thus uranium corrosion is dependent on the presence of moisture and oxygen and results in both solid and gaseous reaction products.

From the point of view of penetrator stability during long term storage under adverse climatic conditions, three environments are of interest; moist air/high temperature; moist air/oxygen depleted (i.e. moist N_2)/high temperature; and salt fog. Weight change data for these environments are measured using standard test procedures and are an indication of general corrosion resistance. Stress corrosion resistance is studied by measuring the time to fracture at various load levels in a selected environment, or determining K_{ISCC} , the threshold stress at which stress corrosion cracking occurs. The data for weight change and stress corrosion tests for DU-0.75 Ti and DU-2 Mo are presented in the following section. In addition, the results of mechanical tests of DU-0.75 Ti and ballistic tests of the GAU-8 (DU-0.75 Ti) and Phalanx (DU-2 Mo) penetrators after environmental exposure are discussed.

DATA

1. Weight Change Studies

Weight changes due to corrosion are conventionally reported in $\text{mg}/\text{cm}^2\text{-day}$. For uniform corrosion this parameter can be related to the depth of penetration expressed as inches per year (i.p.y.). Uhlig (5) states that corrosion rates greater than 0.05 i.p.y. are unsatisfactory for most applications. For uranium this corresponds to a weight loss of $6.65 \text{ mg}/\text{cm}^2\text{-day}$. For metals that pit, such as uranium, weight loss data can only be broadly interpreted; that is, small weight losses concentrated in local areas could result in unfavorable service of the material. Table I summarizes the weight change data for DU-0.75 Ti and DU-2.0 Mo collected from the experimental results of several investigators. Since the corrosion rate varies with time for the experimental conditions examined, the data includes the time at which the weight loss was determined. In one case (reference 8) only the total test time was reported. Figures 1-4 are the weight change time curves for the three environments of interest. In most cases experimental tests were performed using actual penetrators and these are designated in Table I. In the other cases the type of sample is indicated and, where materials were fabricated by several techniques, the minimum weight change is reported.

In moist air GAU-8 penetrators were observed to gain weight up to 18 days due to the formation of an adherent film. Following this time, localized pitting with the formation of a loose powdery oxide was observed (6). For the Phalanx penetrators, only weight losses were observed. These weight losses increased with time and became constant after about 100 days (7).

In moist, hot, deoxygenated air the bare DU-0.75 Ti penetrators were attacked more severely than in air (6). The corrosion was rapid in the first few days resulting in a weight gain at which time oxide spallation took place. This spallation became large enough to cause an

overall weight loss. Fishman and Wishard found that Phalanx penetrators encapsulated in nylon sabots failed in 10 days at 70°C and 95% relative humidity. Thus the corrosion of the molybdenum alloy is also affected by the lack of oxygen.

In salt fog, GAU-8 penetrators were observed to follow a linear weight loss due to the formation of nonadherent oxide and chloride complexes (6). No weight change data was available for DU-2 Mo in salt fog. Thus, although corrosion is initially rapid in moist air and moist deoxygenated air, the corrosion rate levels off in a short time. In salt fog, the more aggressive environment, the weight loss of the titanium alloy continuously increases.

2. Stress Corrosion Studies

Stress corrosion cracking results from the combined effects of mechanical strain and chemical reaction. While no data is currently available on the residual stresses of DU alloys, residual stresses in any metal can be as high as the elastic limit of the metal (11). These internal stresses coupled with an adverse environment could result in cracking of penetrator materials.

DeJarnette and Fishman (12) have measured the time to failure of four point bend specimens of DU-0.75 Ti and DU-2 Mo (cross rolled to 3 mm thickness in the gamma region and oil quenched) in moist air (95% R.H.), salt contaminated moist air, and 3.5% NaCl solution at 74°C. Table II shows an average of their results at stress levels (σ_f) of 0.5–1.0 σ_y . σ_f is the fiberstress at the center of the tensile face of a four point bend and was calculated using the formula $\sigma_f = \frac{12 DEY}{3L - 4A^2}$ where: D is the specimen thickness, E is Youngs modulus, Y is the deflection, L is the distance between the two outer load points and A is the distance between the two inner load points. In their work the following trends were observed. In moist air at high stress levels, the stress corrosion behavior of DU-2 Mo is somewhat better than DU-0.75 Ti. Time to failure ranged from less than 1 month up to 11 months. In salt contaminated environments the time to failure is significantly less than in moist air environments. At the highest stress levels (i.e. $\sigma_f \approx \sigma_y$) no specimen survived longer than 300 minutes. In NaCl solution the stress corrosion resistance of DU-0.75 Ti is superior to DU-2 Mo. At stress levels of about 0.75 σ_y failure of DU-2 Mo occurred in the order of a few minutes whereas no failure of DU-0.75 Ti was observed for several days. These results are consistent with the experiments of Magnani (13) in which he determined K_{ISCC} for precracked DU-0.75 Ti alloy samples in 100% R.H. air and in 0.01% NaCl solution. K_{ISCC} was found to be greater in moist air. Magnani also observed that penetrators made from the titanium alloy did not crack in either environment during a six month period.

Other tests of Magnani (14) showed that stress corrosion cracking of the titanium alloy was transgranular in both laboratory air (<10% R.H.) and in 50 p.p.m. chloride-solution. Cracking of the 2% molybdenum alloy was transgranular in laboratory air, however, intergranular attack was observed in salt solution. Intergranular attack usually results in more severe cracking.

Thus evidence shows that at high stress levels the stress corrosion resistance of DU-0.75 Ti is superior to DU-2 Mo in salt environments but approximately equivalent in moist air. One further comment, however, should be made regarding the work of DeJarnette and Fishman. Figure 5 shows the results of their stress corrosion tests for DU-0.75 and DU-2 Mo in a salt contaminated environment. An envelope has been drawn around the data for each specimen

and the results are superimposed. Examination of Fig. 5 shows that in salt contaminated moist air the time to failure curves level rapidly at stress levels of about $0.4 \sigma_y$ for the DU-2 Mo alloy. This levelling is observed for DU-0.75 Ti at much lower stress levels i.e., $\approx 0.18 \sigma_y$. Thus while the DU-0.75 Ti alloy is more resistant to stress corrosion at high stress levels in the salt contaminated environment, it is susceptible to cracking at much lower stress levels than the DU-2 Mo alloy. Residual stress measurements appear to be critical in evaluating these alloys for stress corrosion resistance.

3. Mechanical and Ballistic Studies

While it has been reported, Sandstrom (8), that the ballistic performance of uncorroded DU-2 Mo and DU-0.6-1.2 Ti penetrators is comparable, the effects of corrosion on the mechanical and ballistic properties of the alloys should also be considered. Several experiments have been performed.

Weirwick (15) has tested the effects of corrosion on the fracture loads and ductility of buttressed grooved XM 774 penetrators (DU-0.75 Ti). Uncoated, nickel electroplated ZnCrO₄ coated, and aluminum shrouded samples were mechanically tested after exposure for one month in 95% R.H. air, distilled water, and 5% NaCl solution. In the most aggressive environment (NaCl) only moderate corrosion, with no dimensional changes, was observed on the uncoated samples. Mechanical tests indicated no significant changes on fracture loads and elongation. Although corrosion was not observed on the coated samples, all showed a lower load bearing capability when the nickel electroplate was present. In NaCl solution coated samples showed a 9-10% decrease in fracture load. It is suggested that these results can be explained by presuming a galvanic reaction of nickel and uranium, despite the zinc overcoat, with the production of hydrogen. The hydrogen produced egresses into the alloy and causes embrittlement. Thus, although exposure to corroding environments produces no visual corrosion effects, the mechanical properties of the coated specimens tested were changed.

While limited systematic work has been done concerning the ballistic properties of the DU alloys after environmental exposure, two experiments are of interest. GAU-8 penetrators that were severely attacked in salt fog environments were tested at the Frankford Arsenal (16) and Phalanx penetrators were tested after exposure to oxygen and oxygen depleted high humidity environments at 71°C for 15-40 days. Neither of these tests showed a change in ballistic properties following environmental exposure. However since evidence indicates environmental exposure can affect the mechanical properties of DU-0.75 Ti, accelerated corrosion tests followed by the ballistic testing of both alloys should be performed in order to make a ballistic performance comparison.

CONCLUSIONS

The data from environmental tests for the corrosion of DU-0.75 Ti and DU-2 Mo examined in this study failed to reveal conclusive evidence for the preference of one of these alloys in the fabrication of DU penetrators.

A comparative study of the corrosion of the two alloys was done in only one investigation (8) for one environment (moist air). In this environment the total weight gain (adherent oxide and loose product) was 1.3 mg/cm², for DU-0.6-1.2 Ti, and 9.7 mg/cm² for the DU-2 Mo. Using the dimensions of the GAU-8 penetrator (47.73 cm², 300 g) the total weight loss in 147 days would be 0.021% for the DU-0.75 Ti alloy and 0.15% for the DU-2Mo alloy. Presuming

that the weight loss is constant after 150 days for both alloys and since the amount of product is so small, it does not appear that there would be significant dimensional changes due to corrosion on long term storage of the penetrators made from either alloy under these conditions.

Although the corrosion of the DU-0.75 Ti alloy increases dramatically in moist deoxygenated air and salt fog environments (exposure of GAU-8 penetrators in salt fog environment for 30 days results in a copious build up of corrosion products and a total weight loss of about 7% (6).) it would be specious to argue the effect would be the same for the DU-2Mo alloy. Therefore more experimental data is required before a thorough comparison of the corrosion behavior of the two alloys can be made. A knowledge of the behavior in deoxygenated environments and salt fog is necessary in order to decide whether to encapsulate penetrators and how to store them in marine environments.

A knowledge of the stress corrosion behavior of penetrator material is important in evaluating reliability in firing and stability during storage. While DU-0.75 Ti appears to be more resistant to stress corrosion cracking in salt environments at high stress levels the opposite may be true at very low stress levels. A systematic study of the residual stresses in the two alloys for various fabrication processes should be performed and compared with stress corrosion data in order to design penetrators for maximum resistance to stress corrosion cracking.

Short term environmental exposure of DU-2Mo penetrators in moist air or oxygen depleted environments shows no effect on their ballistic properties. The same was found for DU-0.75 Ti exposed to the most severe environment, NaCl, in the uncoated state. Although there was no visual evidence of corrosion, mechanical tests of DU-0.75 Ti showed a decrease in fracture load for coated samples in severe environments. Simultaneous accelerated corrosion tests of both alloys, followed by ballistic testing should be performed in order to draw accurate conclusions concerning the effects of corrosion on their ballistic properties.

Evidence shows that DU-0.75 Ti can be protected from corrosion by sufficiently thick coatings of electroplated nickel (17) galvanized zinc and electroplated nickel-zinc (18). No data concerning the effects of coatings on the corrosion of DU-2 Mo were available, however, there is no reason to suggest that suitable coatings cannot be produced for this alloy. The development of protective coatings could eliminate the problems associated with the corrosion of penetrator materials.

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Table I — Weight Changes for DU-0.75 Ti and DU-2 Mo
in Various Environments

DU-0.75 Ti	Ref	DU-2 Mo	Ref
Moist Air Environment			
92% R.H. 70 C (GAU Penetrator)	6	95% R.H. 74 C (Phalanx Penetrator)	7
(30 days)		(30 days)	
— 1.4×10^{-3} mg/cm ² day		— 0.31 mg/cm ² day	
75% R.H. 74 C (Cast Hot Extruded Rods, DU-0.6-1.2 Ti)	9	75% R.H. 74 C (Cast Hot Extruded Rods)	9
(147 days)			
+ .009 mg/cm ² day		+ 0.07 mg/cm ² day	
Cyclic Temp Humidity (Cast Rods)	10		
(85-95% R.H. 28-71°C 30 days)			
— 0.12 mg/cm ² day			
Moist Oxygen Depleted Environment			
92% R.H. 70 C (GAU Penetrator)	6		
(30 days)			
+ 2.3×10^{-2} mg/cm ² day*			
Salt Fog Environment			
GAU Penetrator	6		
(20 days)			
— 15.6 mg/cm ² day			
Cast Rods	10		
(23 days)			
— 16.5 mg/cm ² day			
GAU Penetrator	11		
(10 days)			
— 17.8 mg/cm ² day			

*Includes spalled oxide

Table II — Average Times to Failure of DU Alloys
at Stress Levels of 0.5-1.0 σ_y

Environment	DU-2 Mo	DU-0.75 Ti
Moist Air	2×10^4 — 5×10^5 min	5×10^3 — 10^5 min
Moist Air Salt Contaminated	2—90 min	70—700 min
3-1/2% NaCl Solution	< 4 min	> 10^4 min

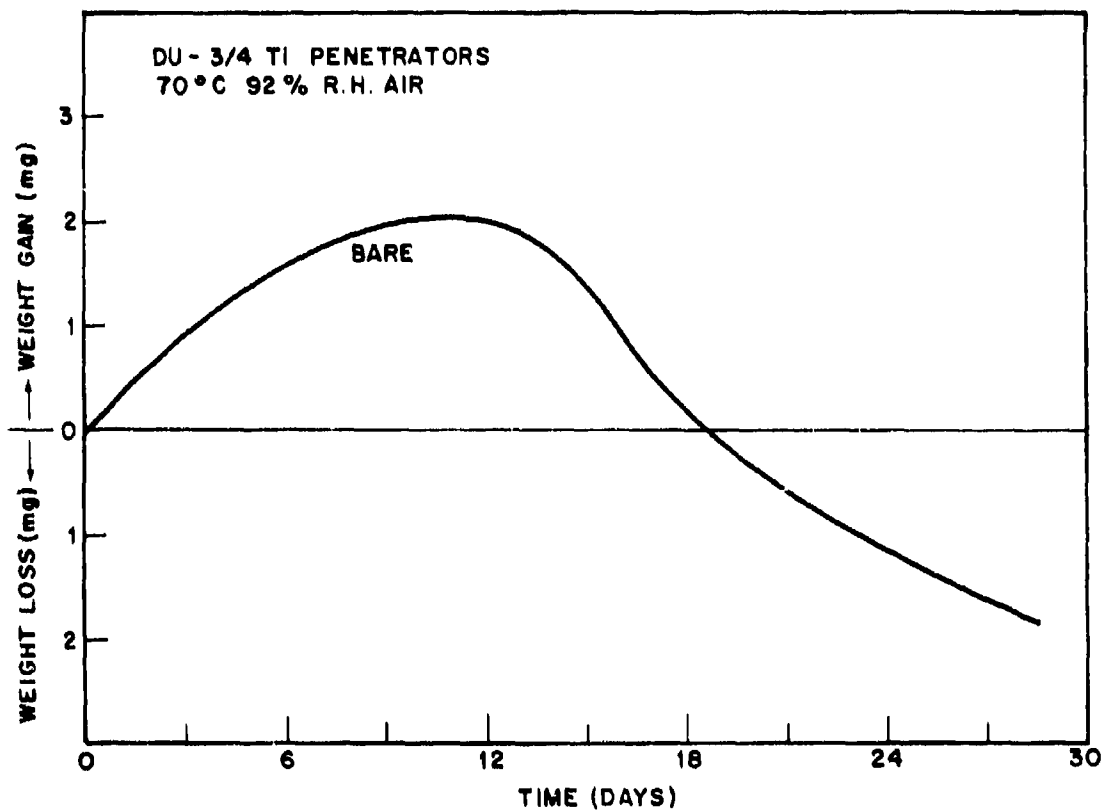


Figure 1 — Weight Change of DU-3/4 Ti Penetrators
in 92% R.H. Air at 70°C (ref. 6)

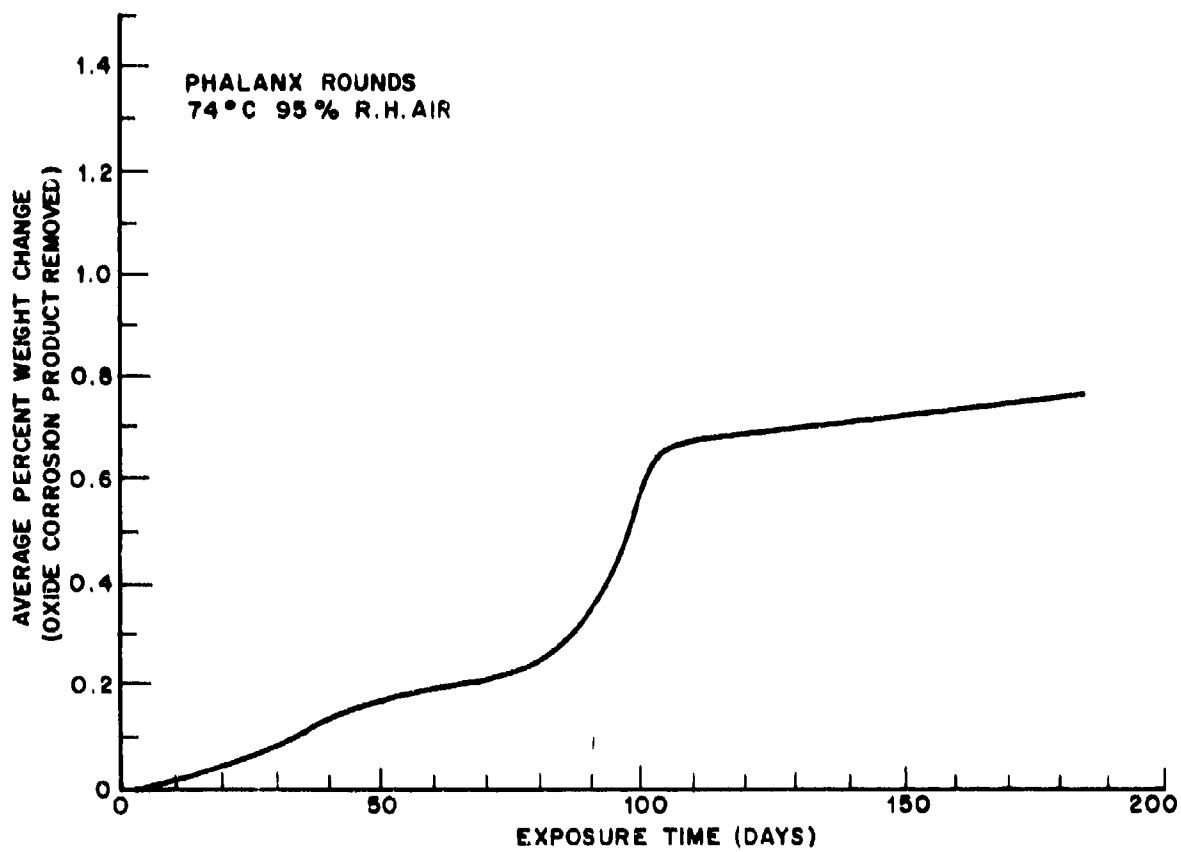


Figure 2 — Weight Loss of Phalanx Rounds in 95% R.H. Air at 74°C (ref. 7)

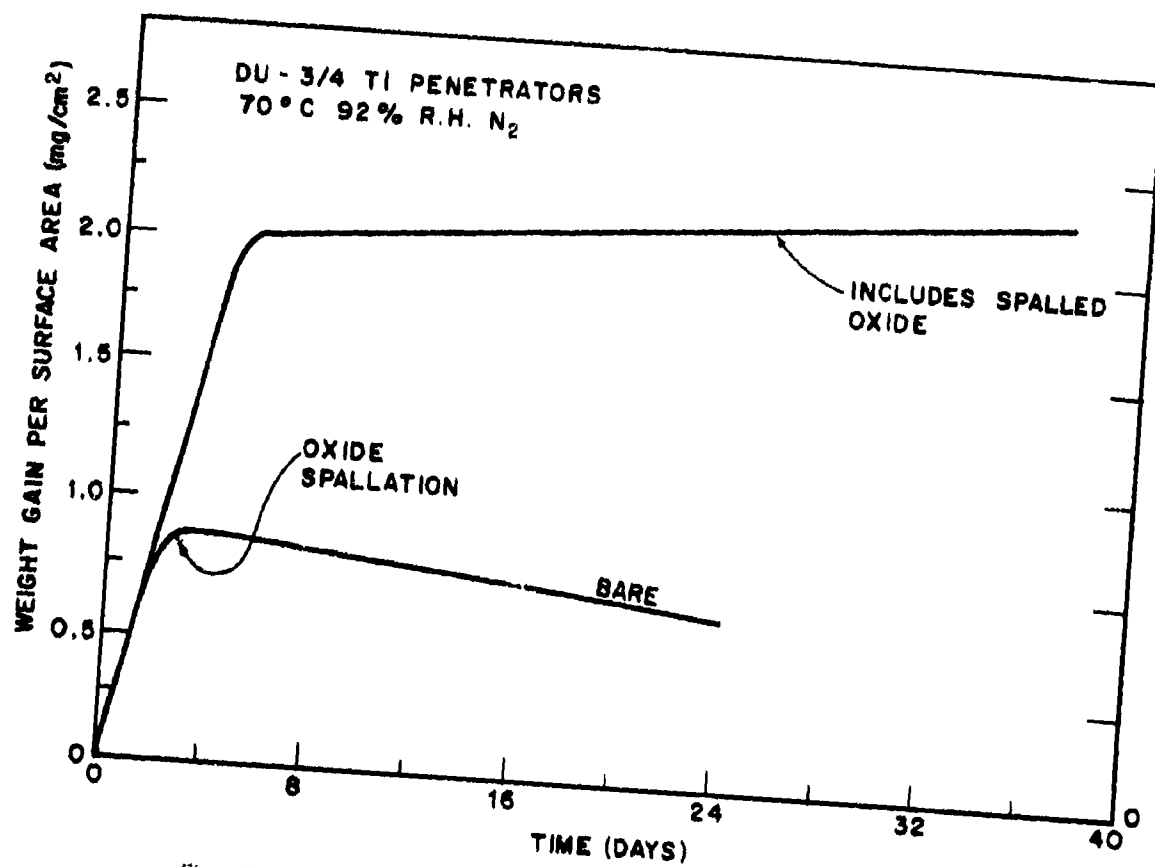


Figure 3 - Weight change of DU-3/4 Ti Penetrators in 92% R.H. Nitrogen at 70 C (ref. 6)

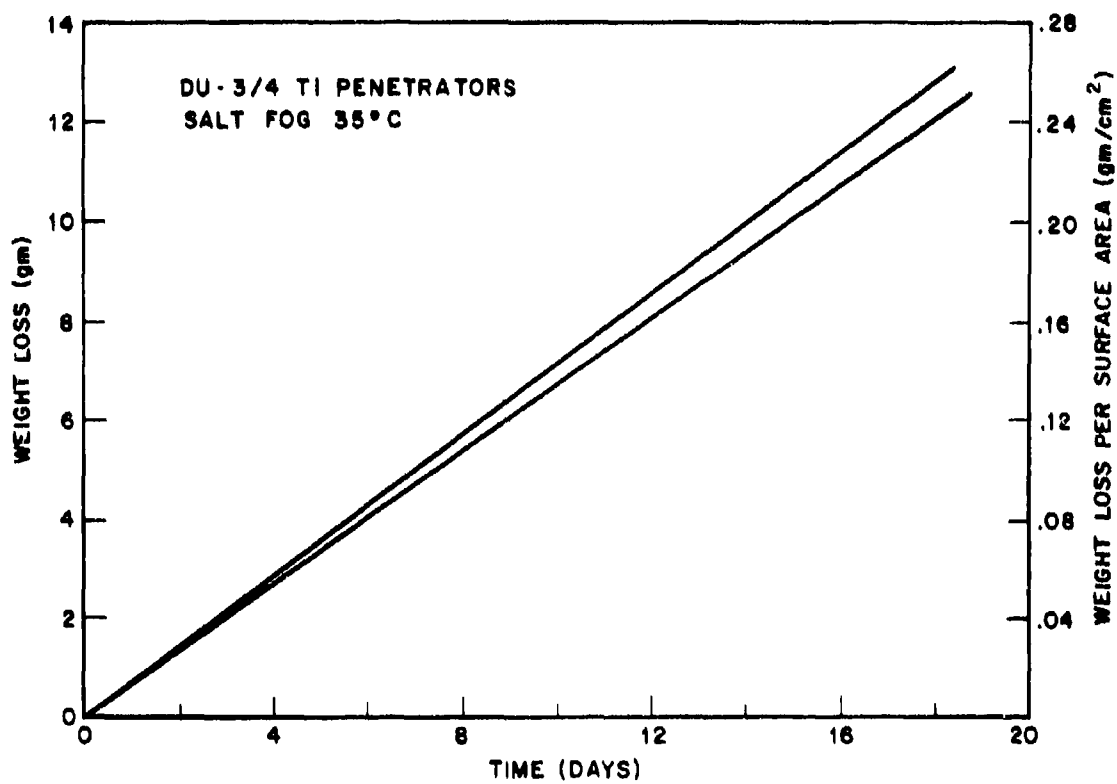


Figure 4 — Weight Change of DU-3/4 Ti Penetrators in Salt Fog at 35 C (ref. 6)

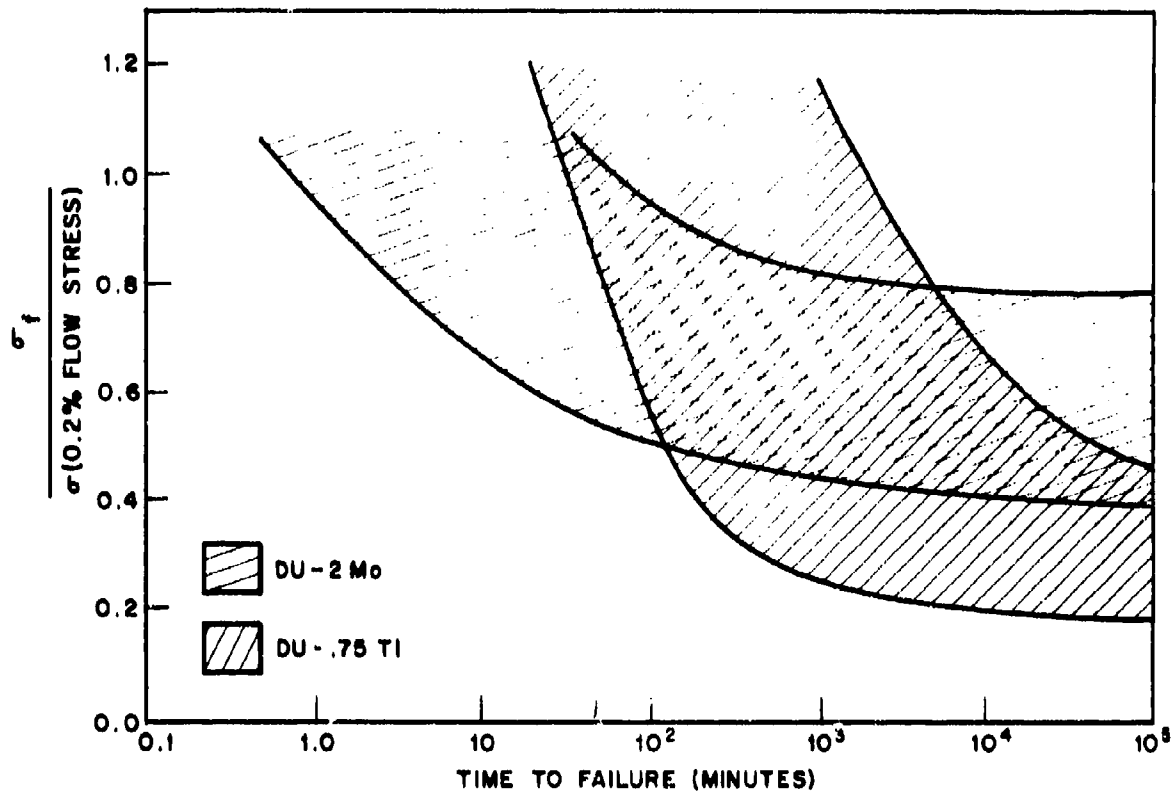


Figure 5 — Times to Failure of DU-2 Mo and DU-3/4 Ti SCC Specimens in a Moist Air Salt Contaminated Environment at 74 C (ref. 12)